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— FINAL REPORT —

# SPACE STATION AUTOMATION STUDY
# AUTOMATION REQUIREMENTS DERIVED FROM SPACE MANUFACTURING CONCEPTS

## VOLUME I
## EXECUTIVE SUMMARY



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GENERAL ELECTRIC

# CONTENTS

# 1.Ø INTRODUCTION

The purpose of the Space Station Automation Study is to develop informed technical guidance to NASA in the use of autonomy and autonomous systems to implement space station functions.

The study organization is shown in Figure 1.Ø-1. NASA headquarters formed and convened a panel of recognized expert technologists in Automation, Space Science and Aerospace Engineering. CAL SPACE was assigned the responsibility for study management, and for convening and directing a University/Industry Committee to produce the Space Station Automation Plan. A Senior Technical Committee, chaired by Dr. Robert Frosch, was appointed to provide top level technical guidance.

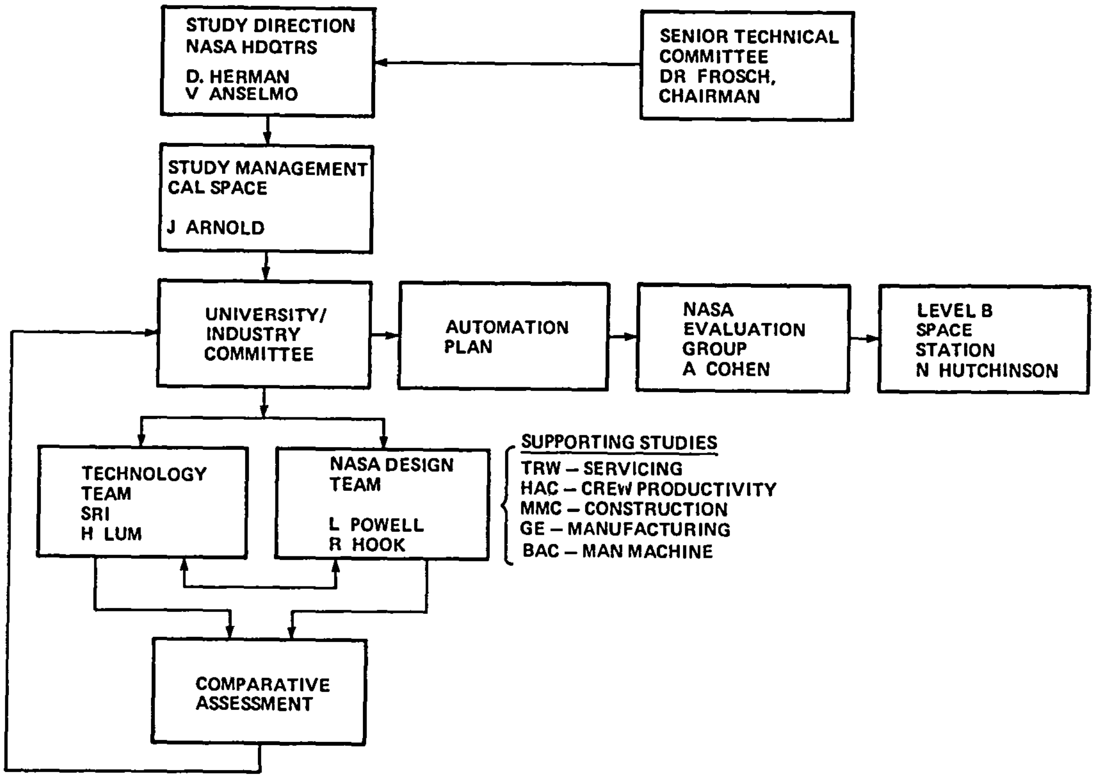



Figure 1.Ø-1. Space Station Automation Study Organization

SRI International was assigned to produce quality focused technology forecasts supporting panel analyses and guiding system concept design.

A NASA Design Team was convened to study the automation of remote space operations to produce innovative, technologically advanced automation concepts and system designs which will strengthen NASA understanding of practical autonomy and autonomous systems. Five Aerospace Contractors, TRW, GE, HAC, MMC and BAC, were assigned to this team.

The General Electric Company was assigned to assess automation technology required for remote operations, including manufacturing applications. In carrying out this assignment, GE assessed over one hundred potential Space Station missions through an extensive review of proposed Space Station experiments and manufacturing concepts. Subsequent meetings of the NASA Design Team resulted in the direction to proceed with in-depth development of automation requirements for two manufacturing design concepts:

(1) Gallium Arsenide Electroepitaxial Crystal Production and Wafer Manufacturing Facility

(2) Gallium Arsenide VLSI Microelectronics Chip Processing Facility

Figure 1.Ø-2 provides a functional overview of the ultimate design concept incorporating the two manufacturing facilities on space station. For the purpose of this study, the concepts were studied separately. This separation allowed conclusions and results to be determined in independent time frames without dependent cross ties.

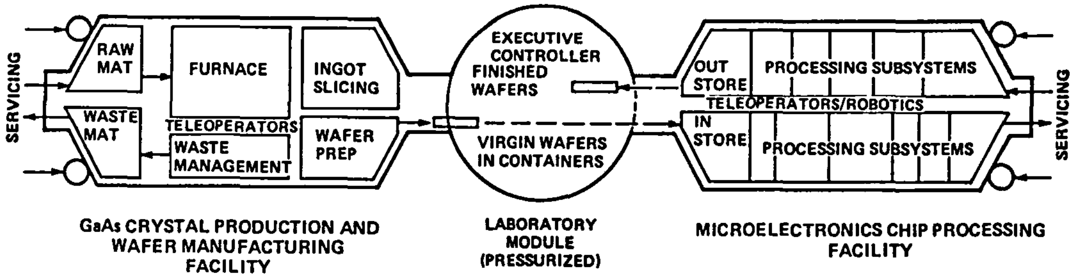



Figure 1.0-2 Overview Of The GaAs Manufacturing Facilities Concepts

Each facility would be developed in an evolutionary step-by-step process. As they are developed, more and more automation would be incorporated, evolving towards a full automation, including maintenance, repair and refurbishment functions.

Ultimately, in the year 2000 + time frame, it would be logical that both facilities could be mated to a common, standard space station pressurized laboratory module. The part time crew would tend the two facilities from the laboratory module, where all computer functions of process control and data display would be performed, and quality control checks and management of the finished products accomplished. Either or both facilities could be operated remotely from the Space Station, however, on separately powered, unmanned free-flying or tethered platforms, with control and data flow accomplished by RF communications with the Space Station or with ground facilities.

Both manufacturing facilities would be contained in enclosed structures as shown to help manage waste products and contamination, and to facilitate man-tended repairs and equipment upgrades.

The electroepitaxial process grows crystals in a low temperature furnace into ingots. These ingots, typically three to five inches in diameter, are then sliced into very thin wafers. The process provides defect free Gallium Arsenide (GaAs) wafers when accomplished in a gravity-free environment. In the second concept, many Very Large Scale Integrated (VLSI) circuits (chips) are typically processed on each wafer at the same time.

The two concepts were chosen for the main reason that they both require a very high degree of automation, and therefore involve extensive use of teleoperators, robotics, process mechanization, and artificial intelligence. They cover both a raw material process and a sophisticated multi-step process and are therefore highly representative of the kinds of difficult operation, maintenance, and repair challenges which can be expected for any type of space manufacturing facility. The automation techniques which would be developed for these space missions will provide direct benefits in the design of future ground-based automated factories to be used for a wide variety of materials processing and manufacturing applications.

Supporting reasons for selecting the two concepts are:

(1) There is a growing demand for faster, larger, and radiation hardened Integrated Circuits for which Gallium Arsenide has superior characteristics over silicon.

(2) An ultra-clean environment is necessary for efficient electroepitaxial crystal growth (ECG) and manufacturing of GaAs products. Additionally ECG requires a microgravity environment. On earth, ECG can only grow crystals of small size and value because of gravity-induced convection currents.

(3) The two concepts are compatible with each other. Although the Crystal Production/Wafer Manufacturing Facility could probably be flown five years before the Microelectronics Chip Processing Facility, eventually the product of one would provide the wafers to be processed into chips by the other.

The study results, although specifically addressing crystal growth and chip production, identify generic areas which will require significant further study for any planned future manufacturing in space. While cost analysis is beyond the scope of this report, the economics and benefits of any space manufacturing facility must be closely analyzed. The success of Space Station will be determined to a large extent by the programs ability to stimulate development of advanced technologies and fully develop the commercial potential of space. Advanced technologies for the automation of maintenance, repair, and refurbishment activities, as well as contamination control and waste removal represent major technological challenges to any space based manufacturing facility. Advanced designs of space manufacturing facilities will employ a high degree of automation, however the initial designs will be based on state-of-the-art hard automation such as terrestrial factories are employing and will grow and evolve as space and terrestrial technologies mature.

<u>The unique aspects of a space manufacturing facility compared to a similar terrestrial factory, include the inability to bring in technicians and specialists for maintenance and malfunction repair. Therefore the advanced automation technology requirements identified by the study are those systems required to remotely monitor, diagnose, and automatically reconfigure, maintain and repair in the event of malfunction.</u> These requirements embrace a broad spectrum of enabling technologies ranging from ultimate expert systems for monitoring, diagnosis and reconfiguration to teleoperation and robotic manipulative systems to perform manufacturing, servicing and repair under remote control from either the Space Station or ground.

## 2.0 STUDY OBJECTIVES, GUIDELINES AND APPROACH

The GE portion of the study was led by the Space Systems Division, but also utilized the corporate experience in manufacturing and automation in other GE divisions. The GE work plan is shown in Figure 2.0-1.

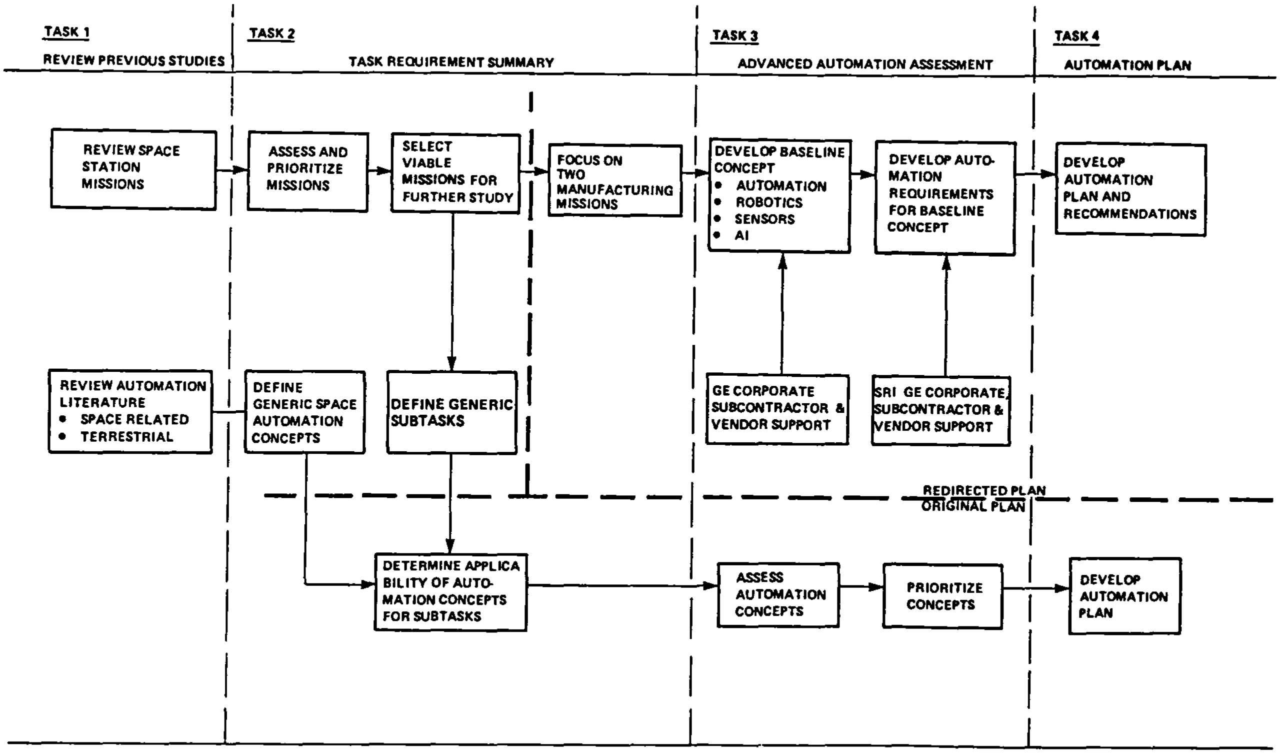



Figure 2.0-1 GE Space Station Automation Study Work Plan

One hundred candidate missions published in the NASA May 1984 Space Station Mission Requirements Report were evaluated on the basis of automation potential and availability of meaningful knowledge. Numerous reports and technical papers presented in symposia and workshops and as an outgrowth of funded studies were also reviewed. As a result of this review the two concepts defined on page 2 were chosen for further development. In order to define automation requirements for these concepts extensive

knowledge of the current manufacturing processes and development of space based designs was necessary.

Data was provided by Microgravity Research Associates (MRA) on the GaAs Electroepitaxial Crystal Growth (ECG) experiment production unit planned for seven STS missions. MRA assisted GE in developing a baseline concept for the GaAs Crystal Production/Wafer Manufacturing Facility for Space Station.

An in-depth analysis of GaAs microelectronics chip production requirements was developed through evaluation of GE Microelectronics Processing Facilities and work with Dr. Keith Russell at the GE Microelectronics Center. The GE Electronics Laboratory in Syracuse, NY was also evaluated and provided data and background information on the GaAs VLSI manufacturing process and the Molecular Beam Epitaxy experimental laboratory.

Manufacturers of microelectronics processing equipment were contacted and asked for support. VARIAN, APPLIED MATERIALS, PERKIN-ELMER, EATON, GCA, ELECTROTECH and HARRIS all provided valuable literature and information on the design and operation of commercial processing equipment and future products. VARIAN visited GE and assisted in the conceptualization of space based processing equipment designs. GE engineers visited three manufacturers, VARIAN, PERKIN-ELMER, APPLIED MATERIALS, to obtain further insight into process equipment technology for space application.

Design requirements and unconstrained design concepts were developed for the two missions which consisted of defined subsystems, facility layouts, and automation schemes. These were presented at NASA Design Team meetings and with helpful comments and direction from NASA, SRI, and the CAL SPACE Automation and Robotics Panel members, a finalization of the design concepts was undertaken.

## 3.0 STUDY RESULTS

The GaAs Crystal Production/Wafer Manufacturing Facility concept requires a special furnace to provide for crystal growth into ingots, and equipment for slicing and polishing the wafers and placing them into cassettes within containers. Extensive use of robotics and other automation and mechanization techniques is required for handling of the raw materials and waste, processing and handling of the products, and test and servicing functions. The facility would be highly automated, but man-tended for the purpose of managing the processes and for maintenance; both of these functions would evolve into nearly totally autonomous operations through the use of automated servicing and maintenance functions and control by use of artificial intelligence concepts once they are fully developed and proven in space.

The Microelectronics Chip Processing Facility consists of seven subsystems which are based on latest state-of-the-art and conceptualized commercial equipment used for earth-based microelectronics processing. The terrestrial versions of these subsystems are typically stand-alone, separate pieces of equipment, sold by various vendors. Current designs each provide their own computer, software and handling devices. Wafer loading is usually accomplished by people in clean rooms using standardized cassettes each containing about 25 wafers. A vacuum environment must be accomplished individually by each subsystem during most steps of microelectronics processing.

Functions of each subsystem were studied and an evolution into a space version developed. The vacuum provided by space allows a major simplification of all subsystems because the vacuum equipment associated with each subsystem can be eliminated. The resulting ease of equipment access also permits a very high degree of

automation. Instead of individual computers, a distributed but integrated data management system is hypothesized, with control and monitoring accomplished from the laboratory module. Each facility could be either replaced entirely with newer designs over the years, or be upgraded in space.

## 3.1 GaAs ELECTROEPITAXIAL CRYSTAL PRODUCTION AND WAFER MANUFACTURING FACILITY DESCRIPTION

The conceptual design of this facility conforms to design requirements which were developed as follows:

The projected demand for GaAs microelectronics of the quality attainable in the space environment was defined. The results are presented in Figure 3.1-1. Microgravity Research Associates (MRA) provided the reference data for this figure based on their own conservative marketing research study. Because of the possibility for development of other materials and/or processes, a saturation of demand is conjectured. If, as MRA predicts, demand increases, a second, upgraded system can be added.

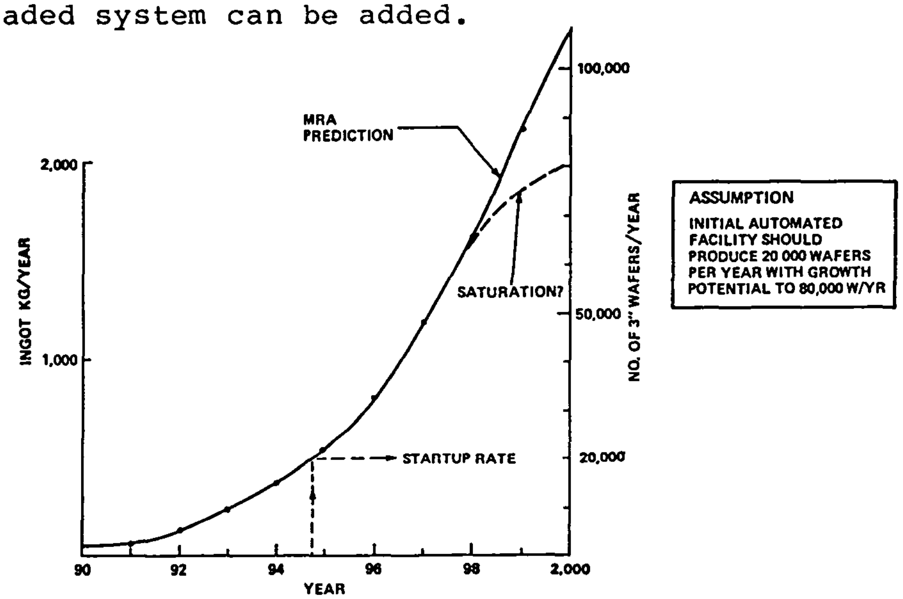



Figure 3.1-1. GaAs Projected Demand

The size of the furnace and size of the ingots to be produced were determined by integrated analyses. An ingot diameter of 3 inches was chosen primarily because furnace power is proportional to area. Five inch diameter ingots are expected to be the earth-based industry norm in the near future, but require nearly three times the power required for producing three inch ingots for the size facility projected. This would be prohibitively high for the IOC space station. Also, because GaAs is extremely fragile, automated handling of three inch wafers will be less risky.

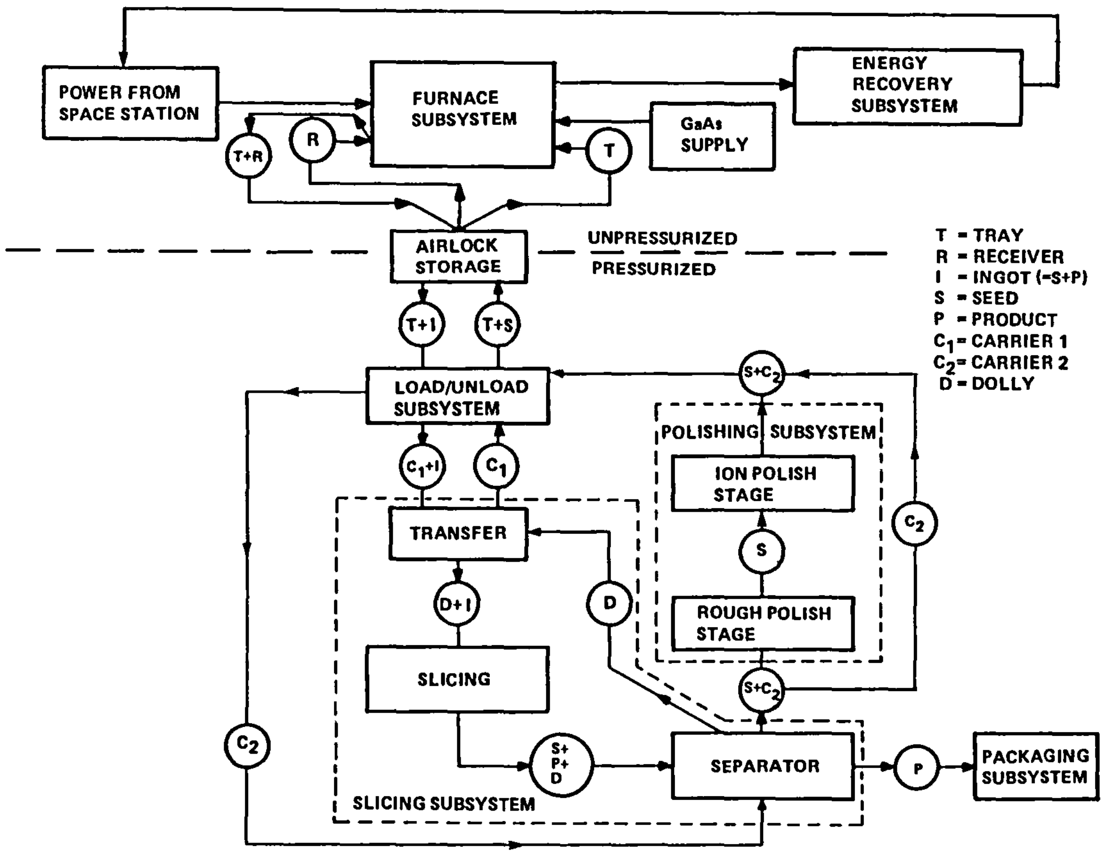
Based on the 3 inch size ingot and the projected demand curve, the furnace was sized to meet a startup capacity in the 1995 time frame of 20,000 wafers/year at 26% utilization, and require one third of available space station power currently planned for the Initial Operational Capability (IOC). Eventual growth to 95% capacity (near continuous operation) would produce 80,000 wafers per year: this would require roughly one third of the projected space station power available by the year 2000, and an optimization of the automation system into one which is almost fully autonomous, including servicing and maintenance functions.

A power recovery system for the furnace is incorporated in the conceptual design. Further study would determine more precisely how much net power would be required. Analyses should also be accomplished to determine if a separate power source would be warranted for each facility, and to determine if other power reducing techniques (i.e., pulsed power) can be effectively employed.

A timeline study determined that each ingot should be grown to a thickness which would yield three wafers per

ingot. This is because energy required increases with ingot thickness, the source crystal can be better utilized for this size growth, and adequate time is allowed for tray refurbishment.

Figure 3.1-2 is a block diagram of the facility. It defines the elements and automation processes required. A conceptual design was accomplished for each element and automation process, and packaged into a standard fourteen foot diameter module, as shown in Figure 3.1-3.




<u>Figure 3.1-2. Crystal Production And Wafer Manufacturing Facility Block Diagram</u>

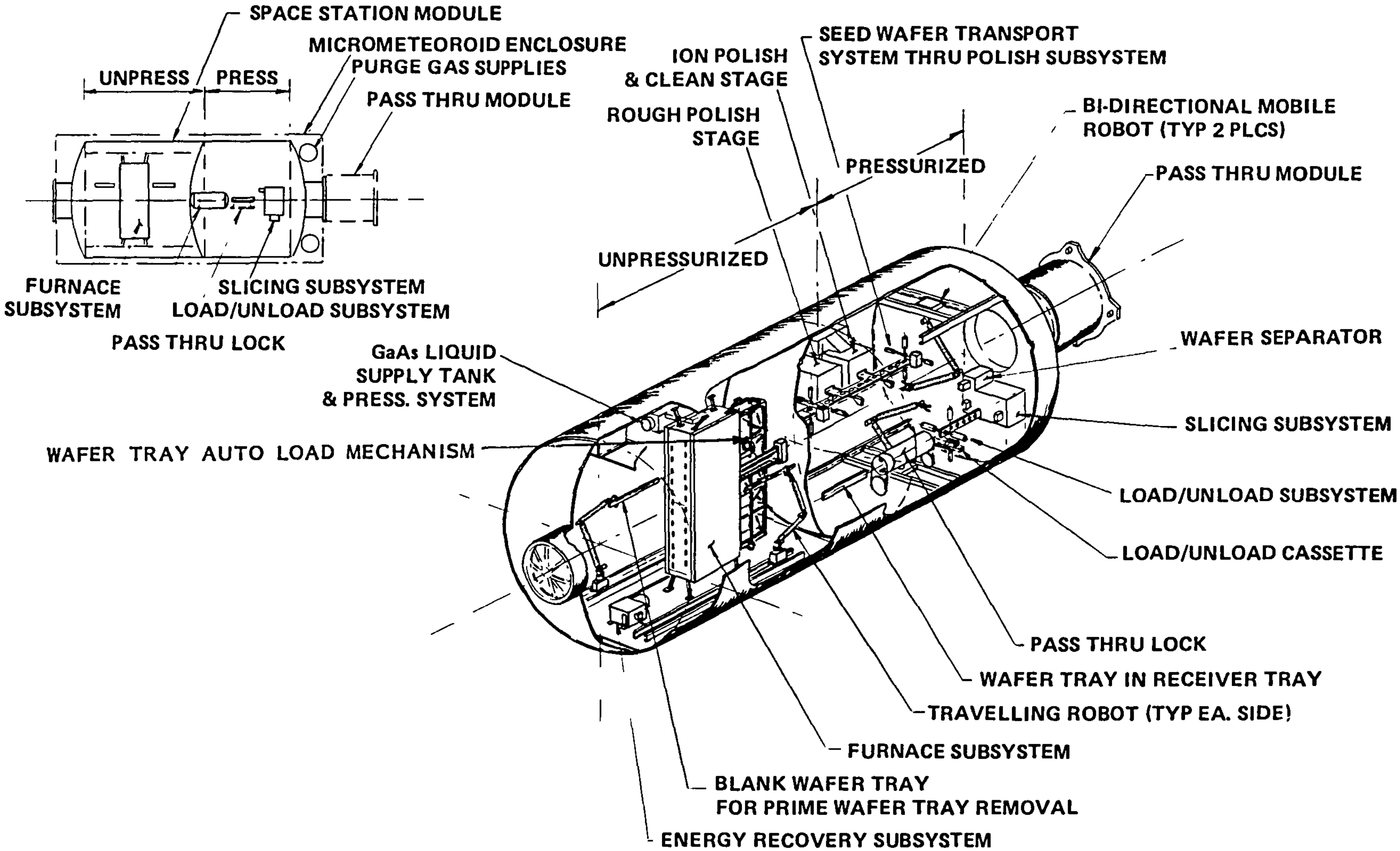



Figure 3.1-3 Crystal Production And Wafer Manufacturing Facility Concept

## 3.2 CRYSTAL PRODUCTION AND WAFER MANUFACTURING FACILITY AUTOMATION REQUIREMENTS

The details of each element and automation process are contained in Volume II. Automation requirements are summarized in Figure 3.2-1.

Much of the automation is in the form of process mechanization schemes similar to those used in factories today for materials handling and manufacturing. However and robots are conceptualized for servicing and maintenance functions, primarily because of their flexibility. Their operating profiles and timelines can be easily altered or upgraded by software, and the configuration of end effectors and their functions can be easily changed for the required applications. In the concepts presented herein, these teleoperators and robots are assigned the added task of materials handling. if it were not for the challenges of maintenance and repair presented by the limitations of the space configuration, the materials handling could be accomplished by straight-forward process mechanization as in earth-based factories.

Artificial Intelligence (AI) will play an increasing role in the operation of this facility, primarily in the areas of process planning and control, and maintenance. The complexities of electroepitaxial crystal growth, and the sophistication of the furnace and slicing equipment warrant an integrated "expert". Expert process and maintenance controllers offer an expanded knowledge-base to aid Space Station crew members in identifying, troubleshooting and handling anomalies in the crystal growth process and associated equipment performance. As conceptualized, the expert controllers would perform the following functions:

| | AUTOMATION FUNCTIONS | SPACE AUTOMATION TECHNOLOGY ASSESSMENT |
|---|---|---|
| ROBOTICS | FURNACE ROOM TELEOPERATOR/ROBOT<br><br>Process Transport<br>o Furnace Load/Unload<br>- Move and align blank trays for unload<br>- Move and align receiver tray for load/unload<br>o Tray/Receiver Transporter<br>- Move tray and receiver from furnace to airlock<br>- Place tray/receiver in airlock fixture<br>- Return from airlock to furnace with tray/receiver combination | These robotic functions are SOA for terrestrial applications, but have not been fully developed and tested in space |
| | Maintenance<br>o Furnace Disassembly<br>- Disassemble furnace to replace source crystal<br>- Reassemble furnace | The difficulty of doing this subtask depends on how much the furnace design can accommodate remote disassembly "tricks of the trade " Maintenance functions will initially require teleoperation but will evolve into an adaptive robot operation |
| | SLICE/POLISH ROOM TELEOPERATOR/ROBOT<br><br>Process Transport<br>o Load/Unload Station<br>- Transfer cassette from load/unload STA to slice STA<br>- Transfer cassette from polish/clean STA to load station.<br>o Slicing Station<br>- Transfer cassette from slice station to shipping STA<br>- Transfer cassette from slice STA to polish STA. | Same comments as above for robotic material handling |
| | Maintenance<br>o Maintenance and Repair<br>- Remove and replace all actuators and mechanisms<br>- Remove and replace all process subsystems<br>- Remove and replace all process units as required | These replacement functions should be easily accomplished as no tight dimension are needed when modules are replaced Teleoperation during initial operation will evolve into higher level robotics with time and experience |
| ARTIFICIAL INTELLIGENCE | PROCESS CONTROLLER<br><br>o Monitor and Control Furnace Power and Temperature<br>o Coordinate Overall Material Process Control<br>o Monitor and Control Process Station Equipment | The process controller has close terrestrial applications for its monitor and control functions Addition of a knowledge base would aid development of a fully autonomous controller |
| | EXPERT MAINTENANCE CONTROLLER<br><br>o Monitor and Flag Abnormal Operation of Equipment<br>o Insulate Equipment Faults, Trouble Shoot, and Develop Best Course of Action | The maintenance AI expert system will need development but terrestrial parallels should exist |

| | AUTOMATION FUNCTIONS | SPACE AUTOMATION TECHNOLOGY ASSESSMENT |
|---|---|---|
| PROCESS MECHANIZATION | FURNACE ROOM<br><br>o No Automation - Except Furnace Load/Unload Mechanisms Could Be Automated Instaed of Robotic<br>o Monitor Temperature, Time and Power Fluctuations<br>o Record Number of Cycles for Refurbishment Time<br><br>**SLICE/POLISH ROOM**<br><br>**o Slice/Polish Room Load/Unload Station**<br>**- Remove Tray from Receiver and Airlock - Positions at Load/Unload Port**<br>**- Remove Ingot from Tray - Place in Cassette**<br>**- Remove Polished Seed Wafer From Cassette**<br>o Slicing Station<br>- Remove Ingot from Tray - Place in Slicing Dolly<br>- Transfer ingot to saw and then to separator<br>- Remove sliced wafers from separation - place in storage can<br>- Remove sliced seed wafer pick from separator - place in cassette<br>o Polish/Clean Station<br>- Remove seed puck from cassette - place in pallet<br>- Move pallet along service track<br>- Move pallet in and out of polish and cleaning station<br>- Position pallet for correct alignment in polish and clean station<br>- Remove polished seed wafer from pallet - place in cassette<br>o Airlock<br>- Open end doors - fill or evacuate airlock<br>- Hold and Release receiver tray<br>o General<br>- Monitor wafer and station temperatures<br>- Monitor cleanliness and pressure | All the mechanisms and controls have terrestrial counterparts, and except for space qualifications can be classified as SOA. |

Figure 3.2-1 Crystal Production And Wafer Manufacturing Facility Automation Requirements Summary

(1) Process Control - The expert process controller interprets assimilated data from process sensors. This information is evaluated against the knowledge base with subsequent diagnosis, and corrective action derived for identified process anomalies. As an example, the disruption of power to the furnace during the growth cycle will require a process planning decision to determine:

- o Which furnace cells, if any, should be cleared, and plan for the recycling of source crystals, and discarding of waste.

- o Optimum schedule to provide ingots which can yield one or two wafers, instead of three, and complete the wafer processing.

(2) Maintenance Control - The expert maintenance controller receives inputs from the furnace and slicing/polishing equipment monitors. As equipment anomalies are interpreted, the controller then flags abnormal operation before hard failure occurs. As the expert system evolves it will ultimately isolate the equipment fault, diagnose the cause, and indicate methods of handling the function.

## 3.3 MICROELECTRONICS CHIP PROCESSING FACILITY DESCRIPTION

Design requirements for this facility are based on the seven mask process for GaAs Very Large Scale Integrated microelectronics manufacturing developed by General Electric. This is a multi-step process which starts with a polished wafer and ends with one which requires only packaging functions which are more cost-effectively performed back on earth, as shown in Figure 3.3-1.

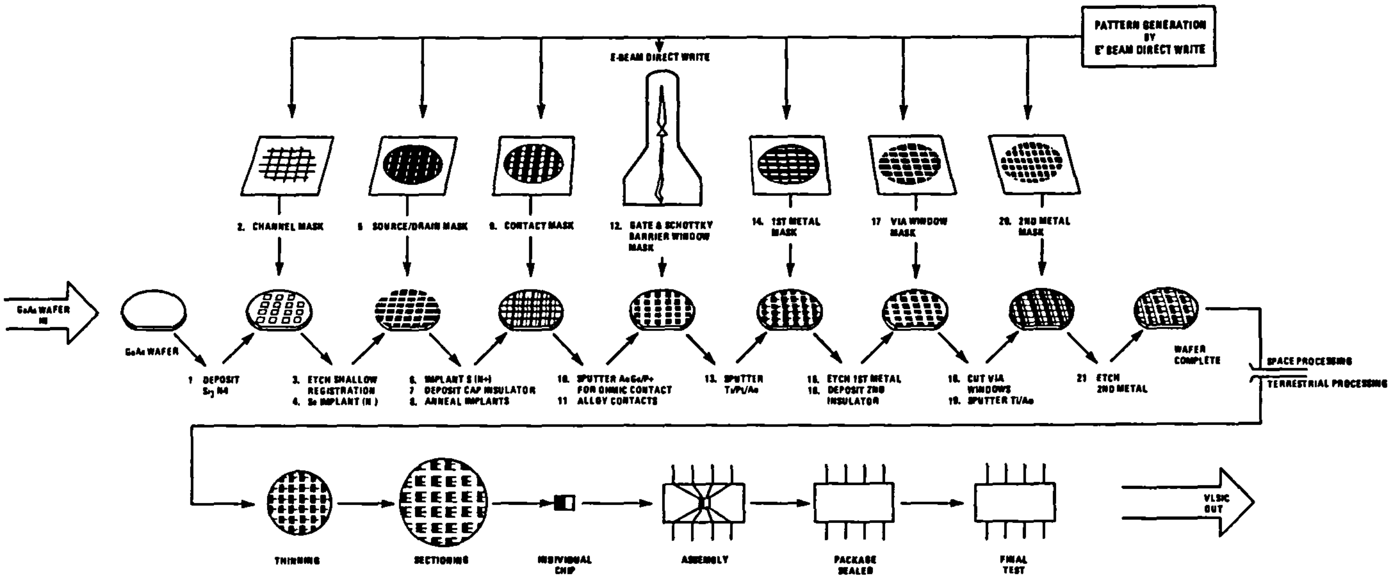



Figure 3.3-1. GaAs VLSI Fabrication Schematic 7 Mask Process

This process is similar to that currently used for silicon chip manufacturing, but requires fewer steps. The current trend is toward totally dry processes, which is by far the easiest way for implementing such a facility in space, because any process involving management of fluids would prove very difficult in the microgravity and high vacuum environment.

Seven subsystems are required to manufacture GaAs chips. These subsystems are diagrammed in Figure 3.3-2, which also defines the individual steps of the process flow in sequence and an estimate of the time required by each subsystem for each step. Note that many passes are required through the E-Beam Direct Writer, while only two or three passes are required for other subsystems. Presuming that only one of each of the subsystems is utilized in the facility design, the automated handling of wafers requires versatile teleoperators and/or robotics, and complex scheduling to accomplish an efficient processing rate.

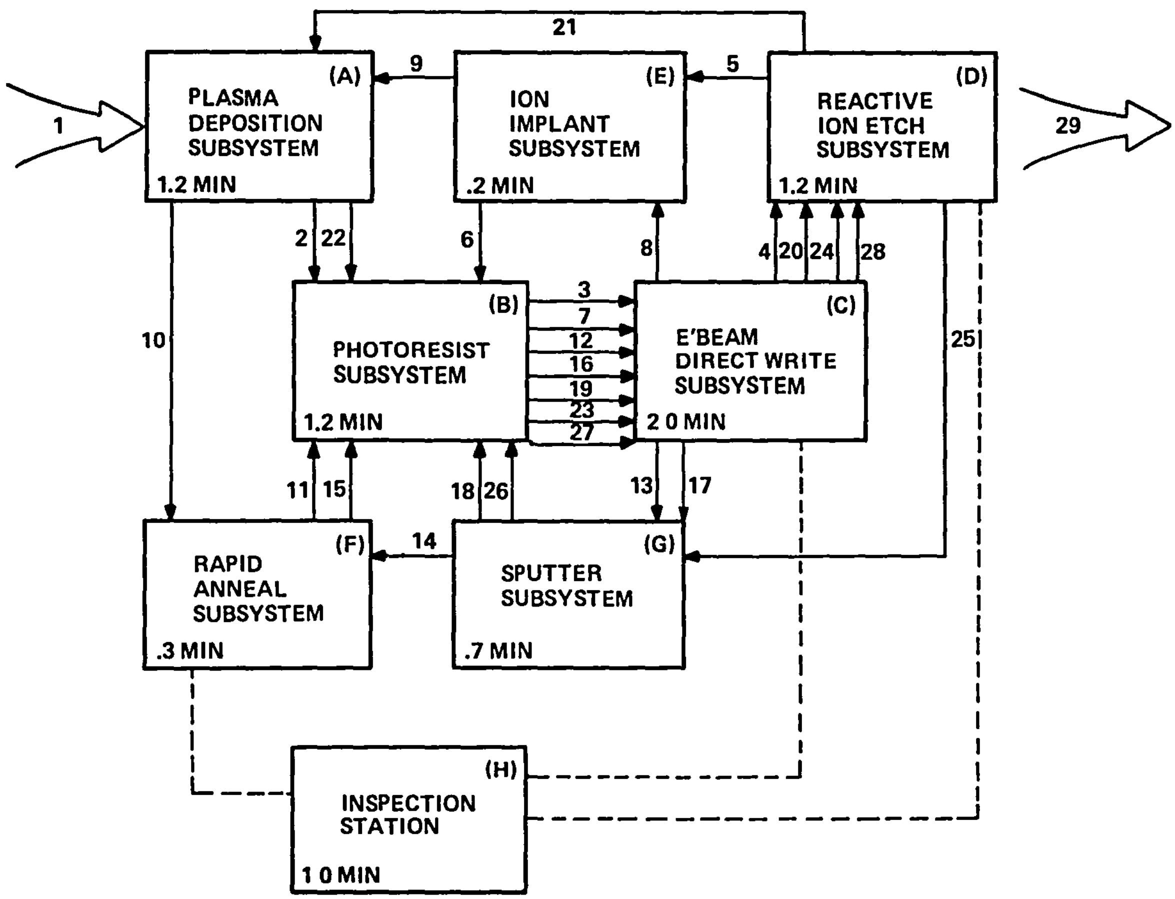



Figure 3.3-2. Microelectronics Chip Processing Flow

All subsystems used in the conceptual design exist today or are in an advanced state of development, but they are in earth-based configurations. Each is made by several manufacturers and usually are delivered and incorporated into microelectronics assembly lines as separate units. Each has their own command and control hardware and software, vacuum chambers, and raw material and waste material handling equipment.

Wafers are generally passed manually in cassettes between the subsystems in clean rooms designed to filter air to the Class 100 to 10 level. Even with this level of cleanliness, contamination is a problem with silicon based chips: GaAs chips will be even more vulnerable, especially if chip density increases tenfold or more as expected.

Several manufacturers, including VARIAN, are developing more fully automated assembly lines incorporating robots and conveyer systems to replace people in the transfer of cassettes from one subsystem to another in an earth based environment, but the vacuum management is still a major hurdle in achieving full automation. This problem would be overcome in the space environment, where a full vacuum facility is possible.

The GE concept for this facility is therefore one which is based on the state-of-the-art subsystems, each without complex vacuum equipment and individualized control hardware and software. Working meetings with each vendor resulted in a repackaging of each subsystem and integration into a fully automated space facility as shown in Figure 3.3-3.

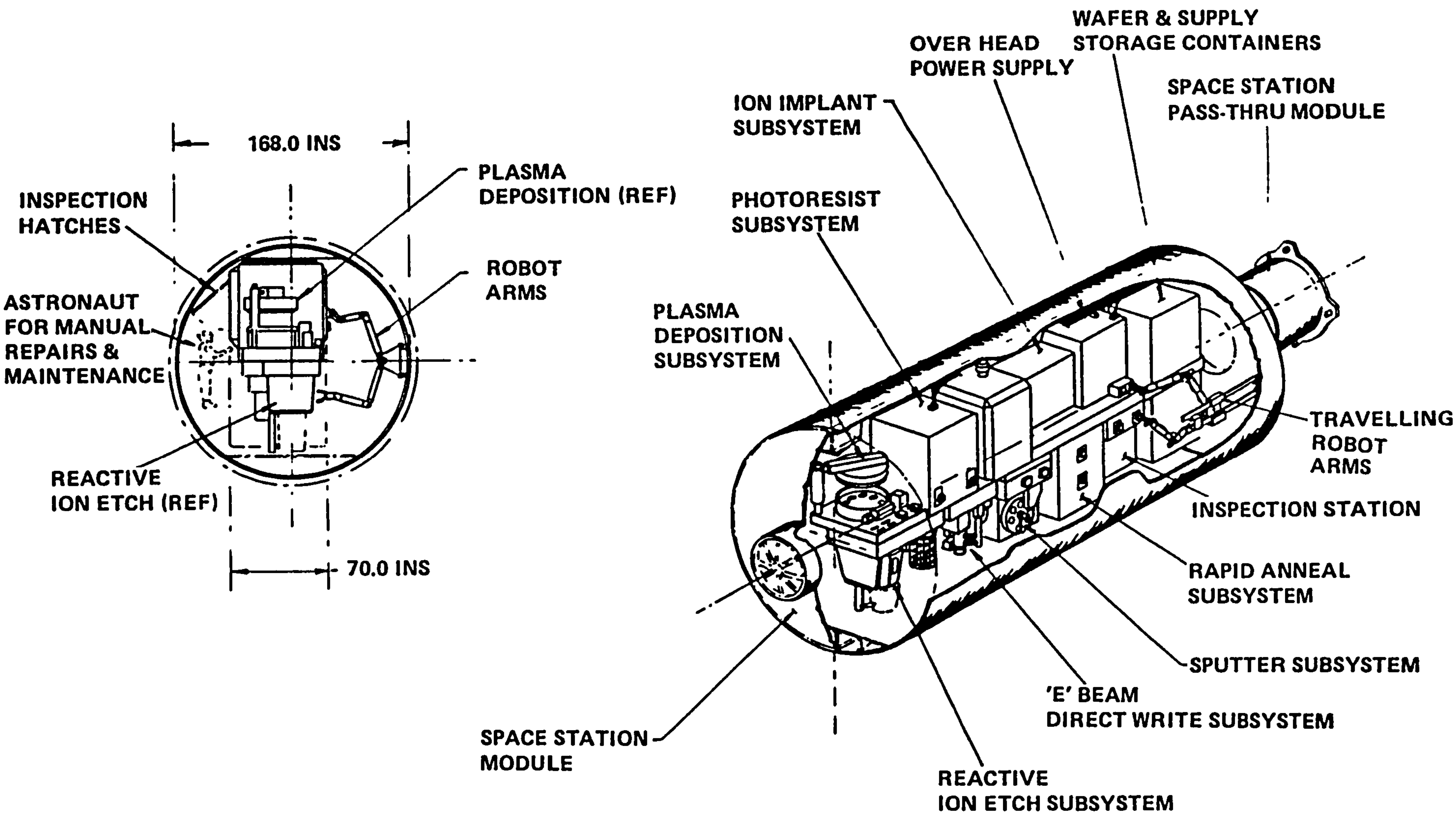



Figure 3.3-3. Automated GaAs Microelectronics Chip Processing Facility Concept

Robotics are used to transport wafers in cassettes to each subsystem in the desired sequence. Control is highly automated, but supervised and occasionally monitored on the ground and in a pressurized laboratory module by a space station crewman. A distributed, fault-tolerant data system is required to manage each subsystem and the robotics and other material handling mechanization.

Crew access is provided for repairs and maintenance as a starting point for this concept. After use in space, the facility should mature, where nearly all repairs, servicing and maintenance would be accomplished through teleoperators and robotics remotely controlled by the software executive controller and the on-board crew.

## 3.4 GaAs MICROELECTRONICS CHIP PROCESSING FACILITY AUTOMATION REQUIREMENTS

Automation requirements are summarized in Figure 3.4-1. Details are contained in Volume II.

In addition to the state-of-the-art mechanization required for each subsystem process, robots are conceptualized for transfer of wafer cassettes between subsystems. These robots would be programmed to work together to move the wafers from subsystem to subsystem quickly and efficiently, and to perform certain servicing and maintenance functions as well. This requires automatic change out of end-effectors and reprogramming of operating profiles.

Software and sensors will be used to control the process most efficiently by optimizing robot movements to prevent interference between robots. For example, the executive controller must know where all arms of each robot are located, its motion, and its current task, and coordinate activities between them.

Each robot is equipped with both vision systems and tactile sensors to precisely locate input and output devices for the subsystems, to retrieve stray containers or fragile wafers, and to perform maintenance functions while the other accomplishes routine processing.

Artificial Intelligence (AI) will be used to identify, troubleshoot, and handle anomalies associated with subsystem processing and maintenance. The complexities of chip fabrication, coupled with the uncertainties associated with space manufacture give rise to the need for an integrated "expert" system. Expert process and maintenance

## ROBOTICS

| AUTOMATION FUNCTIONS | SPACE AUTOMATION TECHNOLOGY ASSESSMENT |
|---|---|
| **PROCESS TRANSPORTERS**<br>• Remove Wafer Cassette from Process Station Unload Area<br>• Transport Cassette to Next Process Station as Determined by Cassette Bar Code<br>• Place Cassettee into Load Area of Next Process Station<br>**INSPECTION TRANSPORTER**<br>• Remove Random Cassette from Process Station Unload Area, as Directed by EPC<br>• Transport Cassette to Load Area of Inspection Station<br>• Remove Inspected Cassette from Inspection Station Unload Area and Transport to Appropriate Process Station | Robotic transport applications are straight forward, however technology for handling the light and fragile cassettes in the space station environment need further development (No terrestrial counterpart) Robot arms must be sensitive to proximity of other arms and process station locations to ensure smooth cassette transportation without collision Vision systems for robotic debris retrieval must be developed |
| **MAINTENANCE TELEOPERATOR/ROBOT**<br>• Remove/Replace Bad Electronic Cards<br>• Remove/Replace Filters, Shields<br>• Remove/Replace Horn Filaments<br>• Remove/Replace Lenses<br>• Refurbish Materials (i e , Sputter Targets Au, Pe, Ti)<br>• Conduct Process Equipment Checks<br>• Perform Unscheduled Cleaning Tasks When Necessary | Maintenance robot applications will require significant development currently, all maintenance functions are performed manually on terrestrial process equipment Robot must be capable of handling moderately complex repair, cleaning, and refurbishment tasks in the microgravity environment Advanced vision and tactile sensors will be required Robotic maintenance applications will evolve from initial teleoperation to an ultimate "intelligent" robot |

## ARTIFICIAL INTELLIGENCE

| AUTOMATION FUNCTIONS | SPACE AUTOMATION TECHNOLOGY ASSESSMENT |
|---|---|
| **EXPERT PROCESS CONTROLLER (EPIC)**<br>• Assimilate Process Monitoring Inputs (Process Sensors, Inspection Station)<br>• Identify Wafers for Inspection<br>• Interpret Process Deficiencies<br>• Identify Effects of Corrective Actions (Based on Actual Models)<br>• Review Effects of Suggested Process Adjustments<br>• Determine Best Course of Action<br>• Implement Required Process Adjustments, Tracks Results<br>• Reconfigure Automation Timeline to Accommodate Process Adjustments<br>• Reforecast Raw Materials Wage and Waste Materials Timeline | EPIC will require full development, as there is no applicable terrestrial system in existence The complexities of chip processing, coupled with the logistic challenges of space demand the timely trouble-shooting and process control knowledge base that an expert system offers. |
| **EXPERT MAINTENANCE CONTROLLER**<br>• Perform Process Equipment Checks as Dictated by Equipment Performance<br>• Flag Abnormal Transient Operation Prior to Hard Failure of Process Element<br>• Isolate Equipment Faults, Troubleshoot, Interpret Best Couse of Action from Knowledge Base | As in the case of EPIC, the expert maintenance controller will require full development The knowledge base will have to account for equipment parameters and idiosyncrasies as well as the effects of the space environment on equipment performance |

## PROCESS MECHANIZATION

**PLASMA DEPOSITION SUBSYSTEM**

- Load/Unload
- Deposit Film (Plasma Enhanced Chemical Vapor Deposition)

**PHOTORESIST PROCESSING SUBSYSTEM**

- Load/Unload
- Perform Water Scrub
- Apply photoresist Coat
- Develop Positive/Negative Resist
- Perforn Bake, Dehydration

**ELECTRON BEAM DIRECT WRITE SUBSYSTEM**

- Load/Unload
- Register Wafer
- Perform Ebeam Direct Write (Vector Scan, Variable Spaped Beam)
- Analyze Write Performance

**REACTIVE ION ETCH SUBSYSTEM**

- Load/Unload
- Control Process Gas Flow
- Control RF Power
- Perform Ion Etch

**ION IMPLANT SUBSYSTEM**

- Load/Unload
- Control Process Gas Flow
- Apply Precise Current to Ion Beam
- Focus and Deflect Ion Beam
- Activate Ion Source
- Control Magnetic Setting
- Analyze Implant Performance (Dose Processor, Oscilloscope, Uniformity)

**SPUTTER SUBSYSTEM**

- Load/Unload
- Perform Sputter Process
- Select and Index Targets
- Measure Film Resistance (Eddy Current Monitor)

**RAPID ISOTHERMAL ANNEALING SUBSYSTEM**

- Load/Unload
- Position Shutter
- Control Radiant Thermal Energy

**INSPECTION STATION SUBSYSTEM**

- Load/Unload
- Position Wafer
- Compensate for Wafer Thickness, Flatness Variations
- Perform Fine Alignment
- Probe Wafer
- Perform System Diagnostics

Listed process mechanizations represent terrestrial SOA capabilities However, terrestrial mechanizations must be adapted to function in microgravity and high vacuum Standardization of process hardware and software becomes a major challenge

- Process Control Software, Language
- Cassette Handling (Load/Unload) Uniformity
- Parts (Mechanical, Electrical)
- Electrical Power

Figure 3.4-1. Microelectronics Chip Processing Facility Automation Requirements Summary

controllers offer a knowledge-base from which the Space Station operator can draw detailed explanations to implement timely process adjustments and equipment repair. As envisioned, the expert controllers would perform the following functions:

(1) Process Control - The process controller assimilates specific online data from subsystem process sensors and inspection probers, and in turn interprets process anomalies and generates appropriate responses. Often the generation of appropriate responses requires simulation of the potential effects of suggested corrective actions. This differs from conventional computer controlled feed back systems in that it can respond to complex situations by applying domain expertise to diagnose and correct deficiencies. The process controller will also make planning and scheduling decisions as process adjustments are implemented.

(2) Maintenance Control - The maintenance controller assimilates real time data from subsystem equipment and consumable monitors to interpret equipment anomalies. As anomalies are identified the expert controller can implement maintenance tests, note possible deviancies and flag abnormal transient operation prior to hard failure. The expert system can isolate a fault, diagnose the cause, and suggest or implement corrective repair.

Periodically, an electrical probe test will be performed on selected finished wafers. This consists of performing up to 73 electrical measurements at various points on a selected wafer to determine quality and process accuracy. The process will be accomplished automatically as it is now, however artificial intelligence techniques need to be applied to efficiently determine the cause of any anomalies and appropriate corrective actions.

## 4.0 CONCLUSIONS

The two manufacturing concepts developed in this study represent innovative, technologically advanced manufacturing schemes. The concepts were selected to facilitate an in-depth analysis of manufacturing automation requirements in the form of process mechanization, teleoperation and robotics, and artificial intelligence. While the cost-effectiveness of these facilities has not been analyzed as part of this study, both appear entirely feasible for the year 2000 timeframe. The growing demand for high quality gallium arsenide microelectronics may warrant the ventures.

The evolution of enabling technologies for space manufacturing will require detailed planning, and coordination with the design team. To facilitate the generation of a responsive automation plan, a list of Generic Space Manufacturing Activities was developed from the McDonnell Douglas Generic Space Activities list (see THURIS Report for activity definitions). This list, as it appears in Figure 4.0-1, was further developed to reflect the degree of automation and associated technology requirements necessary to perform each of the activities over four time phased periods. The figure accurately represents the intimate involvement of man in the process loop at IOC, and the subsequent scaling down of man's role with time to accommodate the ultimate autonomous concept.

Figure 4.0-2 depicts the evolution of automation technologies for space manufacturing from initial development studies, through IOC, to the ultimate autonomous manufacturing facility. This technological progression enhances the stated Space Station technology goals of "maintainability, autonomy, long life, human productivity, evolution, and low life-cycle costs".

| GENERIC SPACE MANUFACTURING ACTIVITIES | 2001 – 2005 | | 2006 – 2010 | |
|---|---|---|---|---|
| | DEGREES OF AUTOMATION | ENABLING TECHNOLOGIES | DEGREES OF AUTOMATION | ENABLING TECHNOLOGIES |
| ACTIVATE/INITIATE MANUFACTURING PROCESS | AR | AI | IR | EXP |
| ADJUST/ALIGN ELEMENTS | AR | AI, VTS, 3DI | IR | AI, VTS, 3DI |
| ALLOCATE/ASSIGN/DISTRIBUTE RESOURCES | AR | AI, VTS | IR | EXP, VTS |
| APPLY/REMOVE SENSORS | HA, AR | SWA, AI, VTS | HA, IR | EXP, VTS |
| COMMUNICATE INFORMATION | HA | SWA | HA | SWA |
| COMPENSATORY TRACKING | AR | AI | IR | EXP |
| COMPUTE PROCESS DATA | AR | AI | IR | EXP |
| CONFIRM/VERIFY PROCEDURES/SCHEDULES/OPERATIONS | HA, AR | AI | HA, IR | EXP |
| CONTROL ELECTRICAL INTERFACE | HA, AR | AI | HA, IR | EXP |
| CONTROL FLUID/GAS INTERFACE | HA, AR | AI | HA, IR | EXP |
| CORRELATE PROCESS DATA | AR | AI | IR | EXP |
| DEACTIVATE/TERMINATE MANUFACTURING PROCESS | AR | AI | IR | EXP |
| DECODE/ENCODE DATA | HA | SWA | HA | SWA |
| DEFINE PROCEDURES/SCHEDULES/OPERATIONS | AR | AI | IR | EXP |
| DEPLOY/RETRACT ROBOT ARM | AR | AI | IR | AI |
| DETECT CHANGE IN STATE OR CONDITION | AR | AI, VTS | IR | EXP, VTS |
| DISPLAY DATA | HA, AR | AI, VTS | HA, IR | AI, VTS |
| GATHER/REPLACE TOOLS/EQUIPMENT | AR | AI, VTS, 3DI | IR | EXP, VTS, 3DI |
| HANDLE/INSPECT/EXAMINE PRODUCT | AR | AI, VTS, 3DI | IR | EXP, VTS, 3DI |
| IMPLEMENT PROCEDURES/SCHEDULES | AR | AI, VTS | IR | EXP, VTS |
| INFORMATION PROCESSING | HA, AR | AI | IR | EXP |
| INSPECT/MONITOR | HA, AR | AI, VTS, 3DI | HA, IR | EXP, VTS, 3DI |
| MEASURE PRODUCT DIMENSIONS | AR | AI, VTS | IR | AI, VTS |
| PLOT DATA | HA | SWA | HA | SWA |
| POSITION COMPONENT | HA, AR | AI, VTS, 3DI | IR | AI, VTS, 3DI |
| PRECISION MANIPULATION OF OBJECTS | AR | AI, VTS, 3DI | IR | AI, VTS, 3DI |
| PROBLEM SOLVING/DECISION MAKING/DATA ANALYSIS | MAN, HA | AI | IR | EXP |
| PURSUIT TRACKING | HA, AR | AI, VTS | IR | EXP, VTS |
| RELEASE/SECURE MECHANICAL INTERFACE | AR | AI, VTS | IR | AI, VTS |
| REMOVE COMPONENT | AR | AI, VTS, 3DI | IR | EXP, VTS, 3DI |
| REMOVE/REPLACE COVERING | AR | AI, VTS | IR | AI, VTS |
| REPLACE/CLEAN SURFACE COATINGS | AR | AI, VTS | IR | AI, VTS |
| REPLENISH MATERIALS | AR | AI, VTS | IR | EXP, VTS |
| STORE/RECORD ELEMENTS | AR | AI, VTS | IR | AI, VTS |
| TRANSPORT ELEMENTS | AR | AI, VTS | IR | AI, VTS |

**DEGREES OF AUTOMATION**

- MAN – MANUAL
- TELOP – TELEOPERATION
- HA – HARD AUTOMATION
- UR – UNADAPTIVE ROBOT
- AR – ADAPTIVE ROBOT
- IR – INTELLIGENT ROBOT

**ENABLING TECHNOLOGIES**

- SWA – SOFTWARE ALGORITHM
- TELEPR – TELEPRESENCE
- VTS – VISUAL-TACTILE SENSOR
- 3DI – 3-DIMENSIONAL IMAGING
- AI – ARTIFICIAL INTELLIGENCE
- EXP – EXPERT SYSTEM

Figure 4.0-1 Time Phased Automation Requirements For Space Manufacturing Activities

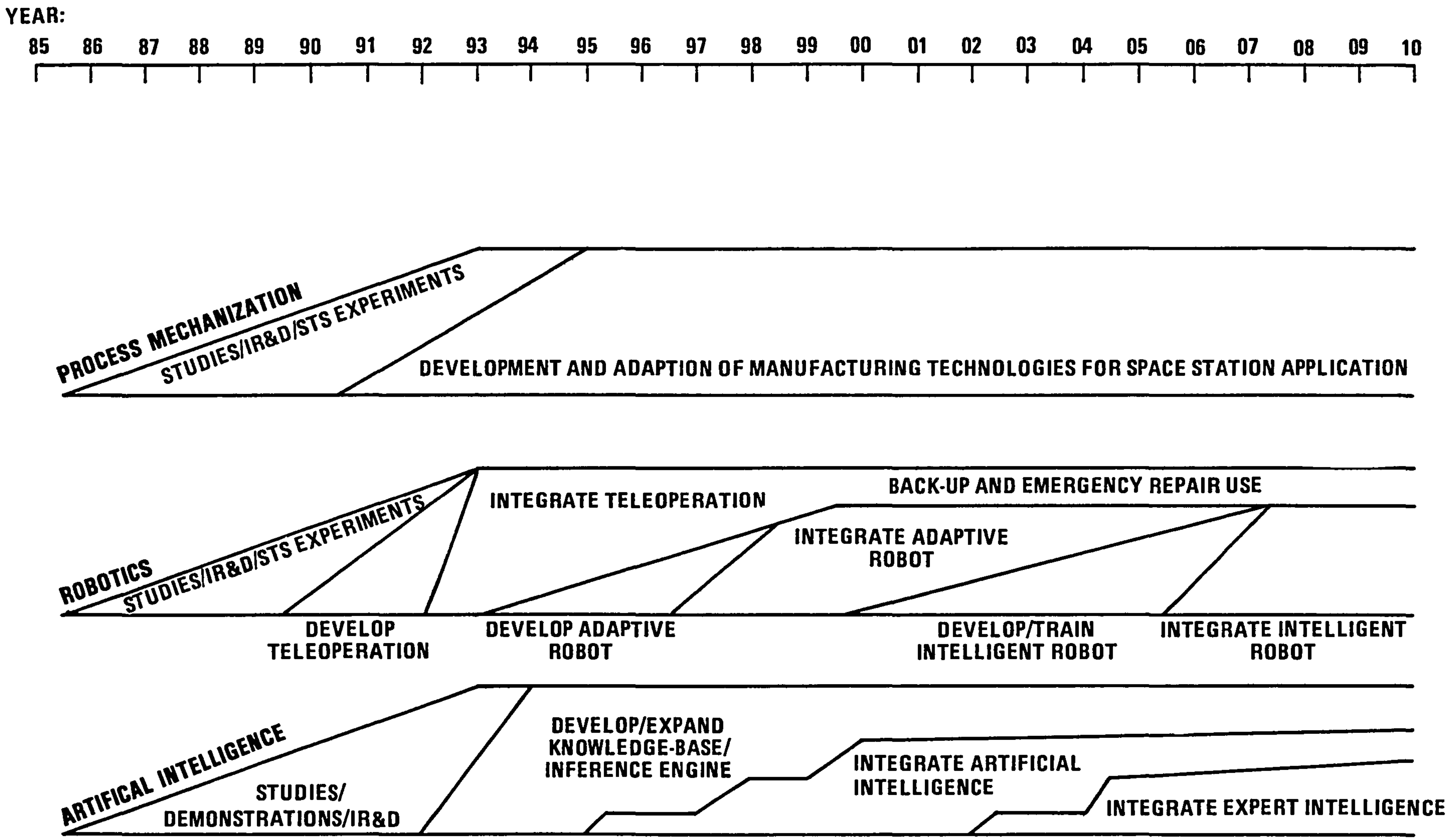



Figure 4.0-2 Evolution of Automation Technologies For Space Manufacturing

Additional work must be accomplished to develop highly automated facilities such as those described beyond the conceptual stage. Such automated equipment is essential for cost-effective space manufacturing.

Very versatile industrial robots are in extensive use today. Those conceptualized for use in space will be of a very different design. They must be able to operate in a hostile environment of hard vacuum with potentially high thermal gradients and radiation. While microgravity allows their design to be lightweight, different kinematics and dynamics will exist. Different approaches to actuation devices and end-effectors must therefore be developed. While the lack of gravity reduces grip and wrist forces, gravity can no longer be used as a helper to catch things or hold them in place. Since the robots must be versatile enough to handle different materials and various repair and maintenance functions, a quick change end-effector replacement system will be required. Many of the complex maintenance and repair functions will be initially done by teleoperators; therefore, feedback devices, including visual and tactile sensors, must be developed well beyond todays' designs.

As more autonomy is developed, the more reliable, serviceable, easily repairable, and accurate the equipment must be. It will be difficult to provide the space station crew the kind of access, information and resources needed to adjust or repair highly automated systems in the confines of a space facility to the degree possible in an earth-base factory.

The major challenge of space manufacturing is maintenance and repairs. Without the automation capabilities to accomplish these functions, manufacturing in space will be unattainable.

Artificial Intelligence can be developed for manufacturing facilities which will provide efficient control of troubleshooting, maintenance and corrective action options. Development of "expert systems" to do the job even better must await expertise to be gained in operating the system during development and in space. This means any program must walk before running by initially providing crew access where possible. As experience is developed, more hardware and software automation can be accomplished, thus making space factories more productive by trading access space for more equipment and materials storage. The space crew will contribute much to this evolution, and will supply much of the expertise needed to develop expert systems for maintenance and repair automation.

Expert systems are very difficult to develop. A data base must be developed and expanded as a facility matures. Therefore more human involvement will be required early in the evolution of each facility. Elements of an expert system can be developed individually, but need to be structured to fit effectively into the total system as it evolves.

## 5.Ø RECOMMENDATIONS

We must "get on with the show": to do so means that research and development must be accomplished in many areas and certain space hardware developed and proven.

The following five specific programs are recommended as a result of this study; they are believed to be essential for many other space manufacturing applications as well.

(1) Space Manufacturing Concepts Development Study
Several manufacturing design concepts, including those described in this report, would be more fully developed to define system requirements, preliminary facility and automation designs, maintenance and repair scenarios, space station interfaces, cost-effectiveness, and evolutionary growth of each through a twenty year period. The concepts would be chosen to assure maximum applicability for automation of manufacturing processes and associated maintenance and repair for all potential space manufacturing applications.

(2) Space Robotics System Experiment
A general purpose, hybrid robot would be designed for experimental evaluation in space. A hybrid robot normally operates under program control with sensory feedback, but for certain applications can be remotely controlled as a teleoperator. A modular design will be considered, so that combinations of different configurations can be evaluated. Self maintainability, the capability of one robot to perform maintenance, repair, and servicing as required for itself or for another robot, will be explored.

Performance and design requirements would be determined using the Space Manufacturing Concepts Development Study as the primary reference, and reviewed by an independent industrial/university committee. After approval, the design would be fully developed, and an experimental robot, together with its controller and a variety of sensor systems, actuators, tools and end-effectors manufactured, tested and flown as experiments on the Shuttle by 199Ø. Experiments would concentrate on maintenance and repair activities, but also investigate materials handling tasks.

(3) Materials Management Study

Space-based handling of the various raw materials required for space manufacturing,and the handling and disposal of waste products and by-products would be studied. Gaseous, liquid and solid waste products would be included and concepts developed for handling of hazardous, valuable and unstable materials in the space environment. Servicing schemes for replenishment and disposal would also be addressed.

(4) Materials Handling Experiments

Experiments in materials handling which are necessary for a variety of manufacturing applications would be flown on shuttle in the 1989-1991 time frame. Included would be experiments in gaseous, liquid, and solids handling of raw and waste materials and by-products, selected from results of the Materials Management Study. Handling of toxic materials necessary for likely space manufacturing systems and collection of dust-like particles resulting from slicing and polishing operations would be candidate experiments. Some experiments would be integrated with the Space Robotics System Experiment.

(5) Space Manufacturing Artificial Intelligence Applications Study

A university/industry team would study specific concepts selected from the Space Manufacturing Design Concepts Development Study to define conceptual artificial intelligence system designs for control, maintenance, troubleshooting, and corrective actions required to operate the facilities. The data management system requirements for these AI concepts would be sized and interfaces with the Space Station Data Management System (DMS) defined thus providing the foundation for full development of Space Manufacturing AI applications. This effort should commence as soon as possible because of the potential impact on Space Station DMS architecture.

Space manufacturing activities must be closely coordinated with other Space Station activities. Impact assessments need to be conducted during Phase B studies to ensure compatibility of manufacturing missions with Space Station operations. Manufacturing interfaces that have been identified as requiring further evaluation by Phase B contractors include power, thermal, data handling, servicing and waste management.

- Power - Further study to determine power distribution impacts on process scheduling; scarring study to accommodate power expansion requirements beyond IOC; assessment of GaAs crystal growth potential for manufacturing solar arrays to create additional/independent power sources.

- Thermal - Study to assess the effects of thermal shadowing on manufacturing processes; trade study to evaluate centralized vs distributed control of temperatures; assessment of the economics of recovering Space Station waste heat energy or solar energy to help drive furnaces.

- Data Handling - Study to determine required levels of language, capacities and rates; projection of data handling requirements for the ultimate manufacturing concept to allow sufficient scarring to accommodate evolving Space Station manufacturing facilities.

- Servicing - Study to assess a universal Space Station approach for raw materials, gas and fluid handling, study to determine problems associated with handling toxic materials/gases.

- Waste Management - Study to resolve waste collection vs dumping trade-offs; evaluation of a common waste collection module to be launched from the Space Station for incineration by the sun.

These studies and experiments will help develop new technologies required for space manufacturing. The studies will also stimulate interest in the manufacturing industries through involvement and understanding of the benefits of manufacturing in space. With the desire of American and foreign industries to reap these established benefits, the future of the Space Station Program will be assured.

**End of Document**